Least Energy-Consumption Real-Time Routing Algorithm Based on Event-Sensitive Node Set

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Abstract —QoS routing algorithm is an important issue to research in wireless multimedia sensor networks (WMSNs). The least energy-consumption and real-time routing policies are addressed in the paper. A novel QoS routing algorithm is proposed to optimize QoS parameters based on event-sensitive node set. This algorithm includes three parts. Firstly, graph *G* of WMSNs is traversed and these nodes whose residual energy is lower than a desired value will be removed from *G*. Secondly, Dijkstra algorithm with energy consumption as metric parameter is used to compute the least energy paths from each event sensitive node to the sink node. Thirdly, if a path destroys the delay upper bound, the least delay path will be computed to replace the least energy consumption path. Its correctness is also reasoned and proved in theories. At last, two simulation experiments are done to test the proposed algorithm.

Index Terms—Wireless multimedia sensor networks, routing algorithm, QoS, theory analysis, simulation

I. Introduction

Wireless sensor networks (WSNs) are comprised of a large number of low-cost, low-power and smart sensor nodes. And its purpose is to collaborate, collect and process environment information in network coverage area, and to sent collecting information to observer [1]. These sensor nodes usually communicate in a short distance and multi-hop method to achieve some application-specific objectives, such as obtaining the simple temperature, infrared, and pressure parameters in the monitored area. Recently, with the requirement of complex environment surveillance, audio, image and video sensor nodes are rapidly introduced to the WSNs and such forms a novel networks, that is, wireless multimedia sensor networks (WMSNs) [2], [3]. In WMSNs, the delivery data include not only conventional simple data but also multimedia data such as image, audio and video, which have strict real-time demand and other quality of service (QoS) requirement. So, multimedia communication brings significant challenges for WMSNs.

In fact, WMSNs is an expansion and extension of WSNs. First of all, as the tradition WSNs, it is resource constraints in four aspects (energy limited, computing power limited, storage capacity limited, communication bandwidth limited) in WMSNs, and it is also the same to WSNs in self-organizing, cooperativity, multi-hops, ubiquitous computing. Secondly, the node number of WMSNs is also large, the network node is deployed randomly, the system is designed for specific applications, the change of network topology is usually frequent, and the state of communications links is also poor in varied case. In spite of those, WMSNs is obviously different from WSNs. WMSNs have much more rich perception ability, and can offer more service kinds in monitoring environment. So, the quality of service (QoS) control must be provided and guaranteed, which is essential and important to WMSNs. Detailly, the nature features of QoS control in WMSNs include: 1) The requirement of QoS control and guarantee is stronger than WSNs; 2) Because of a greater amount of multimedia data transmission, the energy saving/consumption problem is more outstanding and more urgent than WSNs; 3) Due to the unique multimedia data flow characteristics and model, QoS requirements is also higher and more strict than WSNs in processing audio, video, and images data flow; 4) At last, the QoS requirements are diversity because of the application data types being numerous (including two large classes, and six sub-types [2]).

Routing algorithm is responsible for constructing the best communication path to delivery data from sensing nodes to sink node or transferring queries/control packets from sink node to specific sensor nodes [4], [5]. It is playing a more and more important role in the area of communication algorithms and protocols for WMSNs. In essence, the WMSNs routing algorithm for multimedia communication is a QoS-requirement routing algorithm. Those requirements for QoS include end-to-end delay guarantee, bandwidth resource, energy consumption, loss packet ratio and the network lifetime, etc.

Just as the traditional Internet, system structure of WMSNs and its routing also include the plane type and the layered type. In WMSNs, the network nodes are multimedia sensor nodes including images, video and sound monitor function, which makes WMSNs become a multimedia communication network. So, WMSNs have completely different functions and character in communication compared to traditional WSNs. The architecture of WMSNs is showed in Fig. 1. In the figure eleven multimedia sensor nodes A, B, C, D ... H, I, and J are included and G is the multimedia convergence

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node/gateway. As shown in this figure, the multimedia data collected by node A, B, C are compressed, encoded, and fused firstly, then forwarded by node I, J, K; gathered into node G, and at last sent to the manager/user by Internet, GPRS or the other systems.

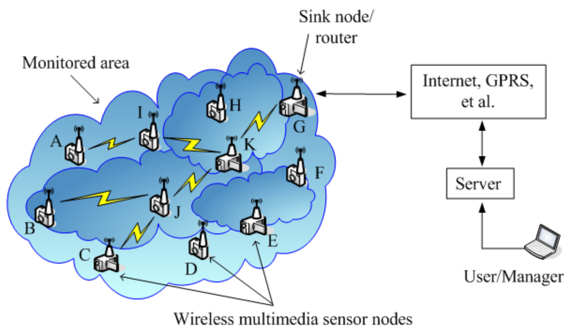


Fig. 1. The architecture of WMSNs and its routing

In wireless sensor networks field, there have existed some algorithms to research routing problem. But most of all tried their best to consider the energy consumption because the energy is scarce to a wireless sensor node. Only a few algorithms consider the QoS support at the same time. Generally, they can be classified into five types: data-centric algorithm, hierarchical/cluster algorithm, location/position-based algorithm, network-flow algorithm and QoS-constrained algorithm. Those typical algorithms include SPIN [6], Directed Diffusion [7], LEACH [8], GEAR [9], Liang [10], and so on.

Among them, QoS-constrained routing algorithms include two types: global link-state route algorithm and stateless/local state route algorithm. Global link-state route algorithm needs all the link/node state information about the network topology to compute the routing path. Stateless/local state route algorithm needs only some state information about the network to compute the routing path, even stateless information. In theory, the advantage of the former is that it can find a path with strict/hard QoS constrain if the path exists, for example, an end-to-end delay guarantee path, which have been done in the conventional Internet/ATM network. Its disadvantage is that it needs too much state information and such is complex to run and store for a large number of nodes (especially, for WMSNs). The typical algorithms include SAR algorithm [11], RTLD algorithm [12], etc. To the latter, its advantage is that it needs only a little state information to find the routing path, and the disadvantage is that it can not guarantee QoS support for multimedia communication. The typical algorithm is SPEED which is an excellent location/position-based routing algorithm, but only provides soft end-to-end delay guarantee [13].

In the paper, a novel routing algorithm is designed by considering both end-to-end delay guarantee and the scarce energy consumption. The paper is organized as follows. In the first section, WSNs, WMSNs and their QoS routing architecture are introduced and the traditional QoS routing algorithm are reviewed. In the second section, several concepts are described and defined in formal language. In the third section, the new routing algorithm is designed to provide end-to-end delay guarantee and minimize the energy consumption for multimedia communication in WMSNs. In the forth section, its correctness and performance of the new algorithm are analyzed in theory by graph approach. In the fifth section, a simulation environment is designed to verify the proposed algorithm according to the current methods in WMSNs, and two simulation experiments are done to explore the algorithm performance in terms of delay guarantee and energy consumption. At last section the conclusions are summarized.

II. Concept and Problem Description

Before discussing the new algorithm in detail, several concepts and the problem definition are introduced, including graph $G(V, E, W)$, event-sensitive node set and the delay-constrained least-energy consumption tree problem.

Wireless multimedia sensor networks can be modeled by a weighted graph $G(V, E, W)$, where V is a set of sensor nodes, E is the set of radio communication links and W is the weight/cost parameter belonged to a specific link/node, which may be regarded as energy consumption, delay and so on. Assumed that the *weight* (u, v) is non-negative for each link $\forall e \in E$, the cost function and the delay function can be written as $Cost(e): E \to R^+$ and $Delay(e): E \to R^+$, where R^+ is a non-negative value set.

Definition 1 (Event-sensitive node set): Given $G(V, E, W)$, when an event i occurs or a query area i is given, we definite the node set as an event-sensitive node set which includes all the sensor nodes which are located in the event/query area with radius R and event center O, and write it $ES(i)$. Formally,

$$ES(i) = \{all\ \ the\ \ node\ \ j \mid Dist(O,\ \ j) < R\}$$

where $Dist(O, j)$ is the distance from node j to the event center O. $ES(i)$ can be shown in Fig. 2.

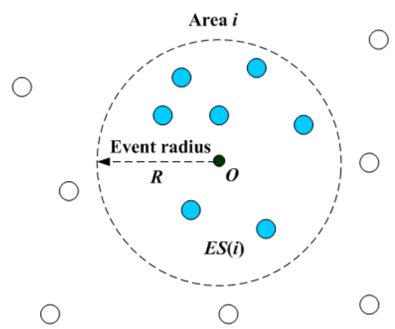


Fig. 2. Event-sensitive node set

Definition 2 (Delay-constrained least energy consumption tree): Given network $G(V, E, W)$, sink node s, event-sensitive node set $ES(i)$ and delay upper Δ_{Delay}, if a tree T covers $s \cup ES(i)$ and meets the following conditions:

$$E_{consumption}(T) = \min\{E_{consumption}(T)\}$$
$$= \min\{\sum_{v\in ES(i)}\sum_{e\in P(s,v)} E_{consumption}(e)\}$$
$$\text{s.t. } Delay(P(s,v)) \le \Delta_{Delay}$$
$$Delay(P(s,v)) = \sum_{e\in P(s,v)} Delay(e)$$
$$(\forall v \in ES(i),\ P(s,v) \in T)$$

so we call the tree T a delay-constrained least energy-consumption tree.

According to the above definition, all the least energy-consumption paths from each node in event sensitive node set to the sink node will form a tree structure, that is, the least energy-consumption tree, in which the sink node is root and all the event sensitive nodes are leaf nodes or on-tree nodes. The problem of constructing the least energy consumption real-time routing tree is NP-complete, which is usually solved by designing heuristic algorithms. Such methods had been done in conventional Internet routing area [14].

In this paper, we concentrated on how to minimize the energy consumption and avoid drying some low residual energy node so that the network lifetime can be prolonged. At the same time, strict QoS support is considered to provide, especially, the end-to-end delay guarantee for real-time communication in WMSNs.

III. Least Energy-Cossumption Real-Time Routing Algorithm

The new algorithm mainly focuses on two goals. Firstly, providing hard/strict end-to-end delay guarantee, this is the most important goal for real-time communication in WMSNs. Secondly, minimizing and balancing the energy consumption so as to prolong the network lifetime. Energy is always a scarce resource in wireless sensor node, and the network lifetime is also a fundamental condition for WMSNs to keep an unblocked communication and provide QoS supports [15].

The algorithm includes three sub-parts. Firstly, the graph $G(V, E, W)$ is traversed and those nodes whose residual energy is lower than a desired value will be removed from G, which will avoid some low energy nodes using their energy up and shorting the network lifetime. Secondly, the Dijkstra algorithm is used to compute the least energy-consumption paths from each event sensitive node to sink node s with the energy consumption as the metric parameter. Because each path for those nodes is the least energy-consumption path to s, the total energy consumption for the whole network will be least. Combining with the first sub part it will prolong the lifetime of WMSNs. At last, if a path destroys the delay upper bound, the least delay path will also be computed by using the Dijkstra algorithm with delay as the metric parameter, and which will be used as the routing path to replace the previous least energy-consumption path. So each path meets the delay upper bound. By those policies the least energy-consumption real-time tree will be constructed. If a loop appears when the least delay path is added to the routing tree, the eliminating loop process will be run to break the loop by changing the parent node simply.

Given graph $G(V, E, W)$, sink node s, delay upper bound Δ and a fixed percent parameter α , the main procedures of the routing algorithm are described as follows.

1) Using the depth-first search algorithm (DFS) to traverse the graph $G(V, E, W)$, and removing those nodes from graph G, whose residual energy is drying and will die out, that is to say, $E_i/E_0 < \alpha$, where E_i is the residual energy of node i, E_0 is the initial energy and α is a fixed percent parameter.

2) Computing the energy consumption for each link e ($\forall e \in G$) by using the energy model that the communication energy consumption is directly proportional to the distance of node i and j, that is to say, $E_{consumption} \propto d^2$, where d is the distance from i to j.

3) Computing the least energy-consumption path $P_{le}(v, s)$ for all event sensitive nodes v (supposed that $\forall v \in ES(i)$) by using Dijkstra algorithm and the results constructing the least energy-consumption tree with the root node s;

4) Computing the least delay path $P_{ld}(v, s)$ for all the event sensitive nodes v ($\forall v \in ES(i)$) with the tree root node s by using Dijkstra algorithm with the delay parameter. If there exist a node v belonging to the event sensitive set and its least delay path destroys the delay upper bound, exiting the procedure;

5) Taking s as the root of the computing least energy-consumption real-time routing tree T;

6) Computing the least energy-consumption real-time routing tree with the delay upper bound Δ by two branch sub-steps for each node u ($\forall v \in ES(i)$). If the delay of the least energy-consumption path $P_{le}(v, s)$ is meet the delay upper bound, the path $P_{le}(v, s)$ will be added into the tree T; otherwise, the path $P_{ld}(v, s)$ will be merged into the tree T (that is, when the delay of the least energy-consumption path $P_{le}(v, s)$ destroys the delay upper bound);

7) If a loop occurs, the eliminating loop process will be run to break the loop by changing node's father node;

8) Repeating step 6 and 7 until all the routing paths for each nodes v ($\forall v \in ES(i)$) meet the fixed delay upper Δ.

By the above algorithm, the least energy-consumption real-time tree T can be calculated out, which can minimize energy consumption to prolong network lifetime and also meets the real time demand according to our previous assumptions. The pseudo codes for the algorithm are as follows, including input, output and the main part of LECRT.

Input: graph $G(V, E, W)$, s, $ES(i)$, α , Δ
Output: the least energy-consumption real-time routing tree T
LECRT (G, s, $ES(i)$, α , Δ)

1. Searching the graph G by DFS, if existing a node w with $E_v/E_0 < \alpha$, then $V= V$-{w} /* *graph G(V, E, W) is traversed and those nodes whose residual energy is low than a desired value will be removed from G*
2. $Q \leftarrow ES(i)$ /* *Q is the node queue in the event* ID/*area i*
3. Computing the energy consumption for each link $\forall e \in G$
4. Computing the least energy-consumption path $P_{le}(v, s)$ from all node u ($\forall v \in ES(i)$) to the sink node s by using the Dijkstra algorithm
5. $T_{Delay} \leftarrow$ Dijkstra(G, s, $ES(i)$, Δ) /* *using Dijkstra algorithm to compute the least delay paths from each event sensitive node to sink node s with the delay as the metric parameter*
6. If $\exists v,\ v \in ES(i)$ *and* $P_{ld}(v,\ s) > \Delta$ then return *Null* /*if *the least delay path destroys the delay upper bound, exiting the process*
7. $T \leftarrow s$ /* *taking s as the root of the least energy-consumption tree*
8. While (Q is not *Null*) Do /**constructing the least energy-consumption real-time routing tree*
9. If $\forall v \in ES(i)$ and $Delay(P_{le}(v,\ s)) < \Delta$ then
10. $Q \leftarrow Q$-{v}
11. $T \leftarrow T \cup \{P_{le}(v,\ s)\}$ /**minimize the energy consumption*
12. Else
13. $Q \leftarrow Q$-{v}
14. $T \leftarrow T \cup \{P_{ld}(v,\ s)\}$ /**meet the delay upper bound* Δ
15. End if
16. If there exists a loop then breaking the loop by changing the parent node
17. End While
18. Return T

(**Note**: $P_{lc}(v, s)$ is the least cost path, ($P_{le}(v, s)$ is the least energy-consumption path and $P_{ld}(v, s)$ is the least delay path from node v to node s.)

IV. Correctness Proof

Theorem 1. Only when there are at least two on-tree nodes on the least delay path at the same time, the loop might appear; otherwise there are no loops in the routing path.

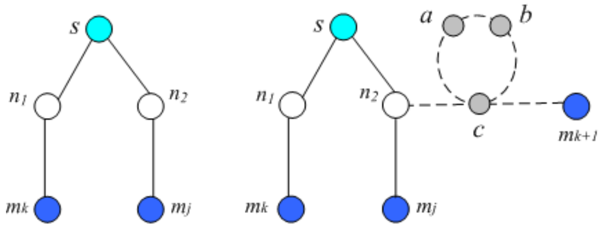
Proof. We can prove it using proof by contradiction. Supposed that the constructed routing path has no loop before node m_{k+1} is considered to compute, and those paths form a tree structure with root s as shown in Fig. 3 (a), black node are the event sensitive nodes, and white node is the on-tree node but no event sensitive nodes. Now, we consider that m_{k+1} is selected to add to the path tree T by on-tree node n_2. Supposed that a loop occur in tree T when there is only one node $v \in T$ and $v \in P_{ld}(m_{k+1}, n_2)$, (that is, v belongs to the least delay path), then the only reason is that there exists a loop in the path outside the constructed tree T, as shown in Fig. 3(b). Supposed the loop is (c, a, b, c), since $P(m_{k+1}, c, a, b, c, n_2, s)$ is the least delay path, we have

$$\begin{aligned} & Delay(P_{ld}(m_{k+1}, s)) \\ & \quad = Delay(P(m_{k+1}, c)) + Delay(P(c, a)) + Delay(P(a, b)) \\ & \quad + Delay(P(b, c)) + Delay(P(c, n_2)) + Delay(P(n_2, s)) \\ & \quad \le Delay(P(m_{k+1}, c)) + Delay(P(c, n_2)) + Delay(P(n_2, s)) \end{aligned}$$

Thus

$$Delay(P(c, a)) + Delay(P(a, b)) + Delay(P(b, c)) \le 0$$

That is, $Delay(P(c, a)) \le 0$, $Delay(P(a, b)) \le 0$ and $Delay(P(b, c)) \le 0$. This is a contradiction with delay and cost being a non-negative value.



(a) An initial tree structure (b) A loop occuring

Fig. 3. The loop occuring in the least-delay path

Theorem 2 The time complexity is $O(n^2)$.

Proof. Provided that the number of network node is n, and event-sensitive node number is m. The time complexity of traversing the graph $G(V, E)$ is $O(n)$. The time complexity of using the Dijkstra algorithm to compute the least delay path and the least energy-consumption path is $O(n^2)$ in the worst case. Especially, step 6 selects a path, $P_{le}(u, s)$ or $P_{ld}(u, s)$ to join the routing tree. The node number of the longest routing path without loop from any one event sensitive node to the sink s is n-1. So the time complexity is $O(m \times n)$ for the number of event-sensitive node m.

Totally, the time complexity of the algorithm is $O(n+n^2+ m*n)=O(n^2)$ in the worst case.

V. Simulation

A random simulation model for wireless sensor network [16], [17] is used to verify the correctness and effectiveness of the least energy-consumption real-time routing algorithm (LECRT). We have used the Microsoft visual basic language to develop the simulation environment. Assumed that 100- 450 wireless multimedia sensor nodes be deployed in a square of $100m \times 100m$ randomly to monitor an event, and the communication radius of each node is the same and equal to 12*m*. If the distance of any two nodes is less than 12*m*, it is deemed that they are adjacent and draw an edge to connect them. Specific simulation parameters see Table I.

An example topology generating by the random simulation model sees Fig. 4. The square area is 100*m**100*m* and the network node number/network scale is 300. The thick node locating in the left top corner is the sink node/query source, the red circle is the event area with radius R equal to 30m and its center point is the event happening place. All the nodes locating in the circle compose the event sensitive node set. The thick and red lines are routing paths for all the event sensitive nodes to transmit information to sink node.

TABLE I: THE SIMULATION PARAMETERS

Parameters	Description	Value
*L*L*	Area of the monitored range	100m×100m
N	Number of nodes/network scale	100-450
m	Number of source nodes	20-90
Delay	Delay for each hop/Relay	0.01s
R	Radius for communication	12m
Cost(·)	Energy consumption	$E \propto d^2$

The delay upper value is set to 0.04s and 0.06s respectively for experiments. The two delay values are closer to the real-time wireless communication situation.

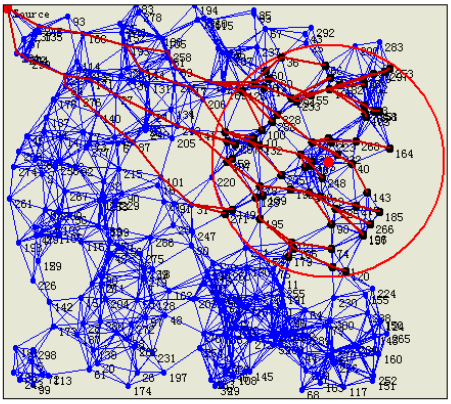
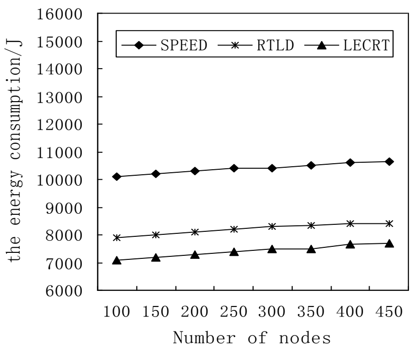
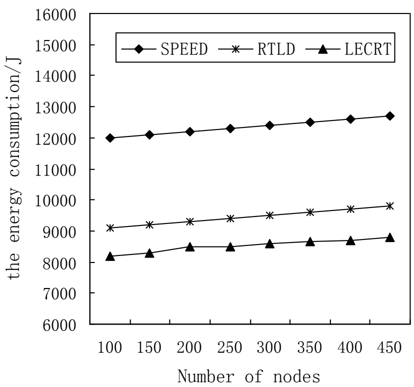


Fig. 4. An example topology



(a) m=20, $\Delta_{delay}=0.06$s.



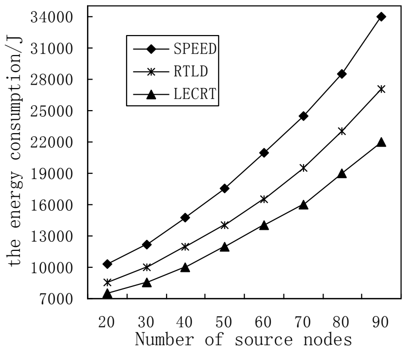
(b) m=20, $\Delta_{delay}=0.04$s.

Fig. 5. Relation of energy consumption and node numbers

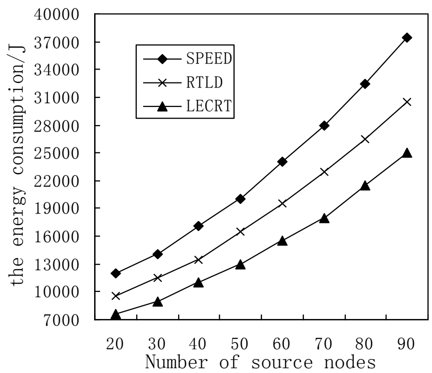
Experiment 1. The relationship of the energy consumption and the node number of network is measured firstly. In this experiment we keep the source nodes a fixed size equal to 20 and the network node number varies from 100 to 450, each time increasing 50. Fig. 5 shows the simulation results. Fig. 5(a) and Fig. 5(b) are the simulation results when delay upper value is equal to 0.06s and 0.04s respectively.

It is clear that the energy consumption of LECRT are lower than the energy consumption of RTLD algorithm and SPEED algorithm in [12] and [13], which is benefited from a low-cost routing tree constructed by Dijkstra algorithm. When the upper delay constraint changed from 0.06s to 0.04s, the difference of energy consumption among three algorithms increases significantly as Fig. 5 (b) shows. LECRT algorithm is relatively better than the two same type algorithms in energy consumption and real time performances.

Experiment 2. The relationship of the energy consumption cost and the signal source node number is measured in the second experiment. The network scale with 200 nodes is fixed, and the number of signal source nodes varies from 20 to 90, each time increasing 10. Fig. 6 shows the experiment results.



(a) N=200, $\Delta_{delay}=0.06$s.



(b) N=200, $\Delta_{delay}=0.04$s.

Fig. 6. Relation of energy consumption and source node numbers

From whether Fig. 6(a) or 6(b), we can see that when source node size is equal to 20, the three algorithms SPEED, RTLD and LECRT have the near performance in energy consumption initially. Along with the increase of node number, the difference in energy consumption is clearer and sharper. No matter how many the source node number there is and how much the delay upper value is, the energy consumption of LECRT is the lowest among all the three algorithms. The energy consumption for RTLD is secondary, and SPEED consumes the most energy.

VI. Conclusions

The QoS routing problem of WMSNs is addressed in the paper by minimizing energy consumption to prolong the network lifetime and optimizing delay constraint to guarantee real-time communication. Based on three proposed assumptions, a novel least energy-consumption real-time routing algorithm is designed for WMSNs. Its correctness is proved and analyzed in theories. As an important part of LECRT, two simulation experiments are done to compare its QoS performance with traditional routing algorithms and subsequently results show that the new algorithm is more excellent than those same type algorithms in end-to-end delay guarantee and network lifetime.

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